Technical University of Denmark

15-THz Tunable Wavelength Conversion of Picosecond Pulses in a Silicon Waveguide

Pu, Minhao; Hu, Hao; Galili, Michael; Ji, Hua; Peucheret, Christophe; Oxenløwe, Leif Katsuo; Yvind, Kresten; Jeppesen, Palle; Hvam, Jørn Marcher

Published in:
I E E E Photonics Technology Letters

Link to article, DOI:
10.1109/LPT.2011.2162059

Publication date:
2011

Citation (APA):
Pu, M., Hu, H., Galili, M., Ji, H., Peucheret, C., Oxenløwe, L. K., ... Hvam, J. M. (2011). 15-THz Tunable Wavelength Conversion of Picosecond Pulses in a Silicon Waveguide. I E E E Photonics Technology Letters, 23(19), 1409-1411. DOI: 10.1109/LPT.2011.2162059

15-THz Tunable Wavelength Conversion of Picosecond Pulses in a Silicon Waveguide

Minhao Pu, Hao Hu, Michael Galili, Hua Ji, Christophe Peucheret, Leif K. Oxenløwe, Kresten Yvind, Palle Jeppesen, and Jørn M. Hvam

***Abstract*—We demonstrate all-optical ultra-broadband tunable wavelength conversion of one-picosecond pulses based on four-wave mixing in a 3-millimeter long dispersion engineered silicon waveguide. In the waveguide, an input pulse with center wavelength at 1600 nm is down-converted by 135 nm (17.3 THz) to 1465 nm. A tuning range of 115 nm (15 THz, from 1465 nm to 1580 nm) of the converted wavelength is demonstrated, while keeping conversion efficiency, pulse shape and pulse width almost unchanged.**

***Index Terms*—All-optical wavelength conversion, four-wave mixing, integrated optics, nonlinear optics, silicon waveguide.**

I. Introduction

Wavelength conversion (WC) in wavelength division multiplexed (WDM) and time division multiplexed (TDM) optical networks is a key technology for future high-bit-rate transport systems because it offers a higher flexibility in traffic management and a dynamic reconfiguration of the optical network [1]. It is desirable that the WC is tunable over a broad wavelength range for wavelength routing and switching. Several all-optical wavelength conversion (AOWC) techniques have been demonstrated using different components including highly nonlinear fibers (HNLFs) [2], photonic crystal fibers (PCFs), $LiNbO_3$ waveguides [3], and semiconductor optical amplifiers (SOAs). Recently, WC in silicon waveguides has also attracted considerable research interest due to compactness, broad bandwidth, and complementary metal-oxide-semiconductor (CMOS) compatibility [4]. As the dispersion of a silicon waveguide can be engineered by the control of the waveguide geometry or shape, broadband conversion bandwidths have been demonstrated in [5], [6]. Previously, silicon waveguides have been utilized to demonstrate WC for data rates from 10 Gb/s to 160 Gb/s [7], [8]. However, in those reports, all the WCs have a fixed pump wavelength, and a tunable wavelength conversion (TWC) was not demonstrated. Very recently, TWC has been demonstrated in a silicon waveguide based on two-pump non-degenerate four-wave mixing (FWM) [9]. In this paper, based on degenerate FWM, we demonstrate TWC of one-picosecond pulses in a dispersion engineered silicon waveguide, which offers a large conversion bandwidth by varying the pump wavelength. A 115-nm tuning range of the converted wavelength within the S-, C- and L- bands is demonstrated.

Manuscript received March 15th, 2011. This work was supported by the Danish Strategic Research Council and the EU FP7 via the projects Nano·COM and GOSPEL, respectively.

M. Pu, H. Hu, M. Galili, H. Ji, C. Peucheret, L.K. Oxenløwe, K. Yvind, P. Jeppensen, and J.M. Hvam are with the DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark (e-mail: mipu@fotonik.dtu.dk).

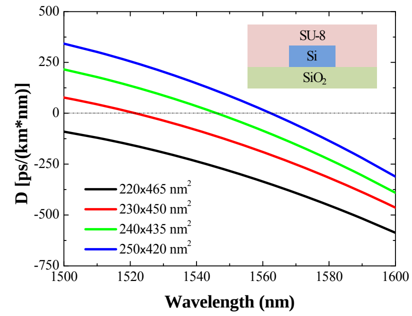

Fig. 1. Simulated group-velocity dispersion D for waveguides with different dimensions for the TE mode. Inset: cross-section of a silicon waveguide.

II. Device Design and Characterization

In parametric WC, the group velocity dispersion (GVD) of a silicon waveguide is of crucial importance since it controls the phase-matching of parametric processes. Due to the strong light confinement in silicon waveguides, the GVD can be tuned by changing the waveguide dimensions [10], [11]. Fig. 1 shows the simulated GVD for silicon waveguides with different dimensions for the transverse-electric (TE) mode. The schematic of the waveguide cross section is shown in the inset of Fig. 1. It is seen that a small difference in waveguide dimensions leads to a shift of the zero-GVD (ZGVD) wavelength. Therefore, the waveguide dimensions should be carefully controlled to get a desired ZGVD wavelength. For TWC with varying pump wavelengths, a broadband phase-matching is necessary to keep the conversion efficiency constant for a fixed signal wavelength. In the low-gain limit, the phase mismatch is dominated by the linear phase mismatch between the signal, pump, and idler waves. And the linear phase mismatch is highly dependent on $\beta_2\Delta\omega^2$, where $\beta_2=-2\pi cD/\lambda^2$ is the GVD parameter at the pump wavelength and $\Delta\omega$ the frequency spacing between the signal and pump waves. The influence of the fourth-order dispersion (FOD) can be neglected in the wavelength range of interest. Then, if the

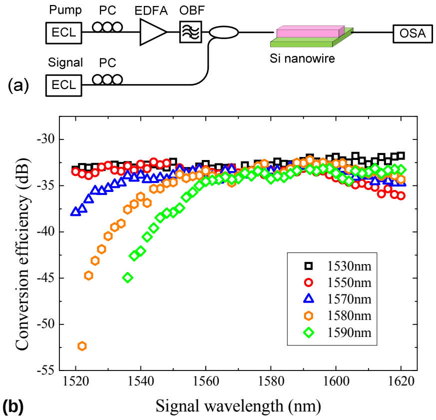

Fig. 2. (a) Experimental setup for the conversion efficiency measurement. (b) Measured conversion efficiencies versus input signal wavelength with different pump wavelengths. The pump power is kept at 20 dBm.

ZGVD wavelength is placed at a suitable distance from the signal wavelength with the pump in-between, as the pump is tuned from the signal towards the ZGVD wavelength, the decreased β_2 together with the increased $\Delta\omega$ may only result in little change for the phase mismatch, thus making the conversion efficiency almost unchanged. For example, to realize broadband TWC for a signal wave in the L-band, we use a silicon waveguide, whose cross-sectional dimensions are 230×450 nm^2, with ZGVD wavelength at 1520 nm (see Fig.1).

The designed waveguide is fabricated on silicon-on-insulator (SOI) material using electron-beam lithography followed by reactive-ion etching (RIE). The 3-mm long silicon waveguide is inversely tapered at both ends, from 450 nm to less than 20nm and covered by a polymer waveguide for efficient fiber coupling [12]. The propagation loss of the silicon waveguide is ~4.3 dB/cm and the fiber-to-fiber loss of the device is ~4 dB. An initial measurement of conversion efficiency for the silicon waveguide is performed in a CW pump-probe configuration as in [13], as shown in Fig. 2(a). Fig. 2(b) shows the measured conversion efficiency for the silicon waveguide as a function of signal wavelength with different pump wavelengths. For a pump wavelength at 1590 nm, the 3-dB conversion bandwidth is estimated to be ~70 nm. As the pump moves towards shorter wavelengths, the conversion bandwidth is increased significantly, as shown in Fig. 2(b). The conversion efficiency is almost constant over 100 nm with a pump wavelength at 1530 nm, indicating a 3-dB conversion bandwidth larger than 180 nm. If a signal wave is fixed at 1600 nm, the conversion efficiency will be constant with varying pump wavelengths and a TWC can be realized over a large pump tuning range.

III. Tunable Wavelength Conversion Experiment

The experimental setups for the TWC of picosecond pulses in a silicon waveguide are shown in Fig. 3. The erbium-glass oscillator pulse-generating laser (ERGO-PGL) produces 10-GHz pulses at 1550 nm with a 1.5-ps full-width at half-maximum (FWHM) pulse width. The 10-GHz pulses are compressed in a 400-m dispersion-flattened highly nonlinear fiber (DF-HNLF) followed by 20 m of standard single-mode fiber. The compressed pulse with a broadened spectrum [2] at the output of the DF-HNLF is split into two pulses (one for the

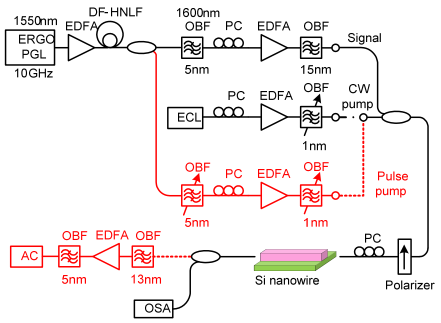

Fig. 3. Experiment setup for the silicon waveguide based all-optical tunable wavelength conversion of sub-picosecond pulses in a silicon waveguide with either CW-pumping or pulsed-pumping scheme.

signal and another for the pulsed pump). For the WC with CW-pumping scheme, the CW pump wave is generated from a tunable external-cavity laser (ECL). The signal pulse is first filtered by a 5-nm optical band-pass filter (OBF), then amplified by an erbium-doped fiber amplifier (EDFA) and subsequently filtered by another OBF. The FWHM of the signal is 1.0 ps. The CW pump, or the pulsed pump, is amplified by EDFAs, and then filtered by another tunable 1-nm OBF. The FWHM of the pump pulses is 2.4 ps. The signal pulse and the CW pump (or pulsed pump) are combined by a 3-dB coupler and then coupled into the waveguide. Polarization controllers (PCs) and a polarizer are used to align the TE polarization into the waveguide. An optical spectrum analyzer (OSA) and an auto-correlator (AC) are used for signal characterization. In front of the AC, the converted signal is extracted by two OBFs with an EDFA in between.

We first measured the conversion efficiency by changing the wavelength of the CW pump while the center wavelength of the pulse signal was fixed at 1600 nm. During the experiment, the CW pump power and the average power of the pulsed signal, at

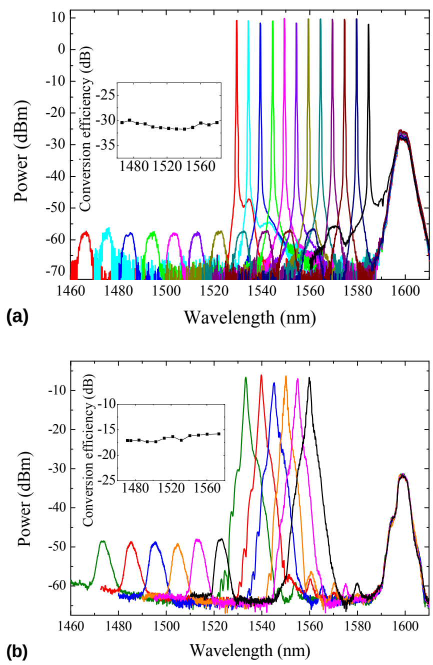

Fig. 4 Measured spectra for picosecond pulse wavelength conversion with (a) CW pump and (b) pulsed pump. Insets show the conversion efficiency versus wavelength in different pump schemes.

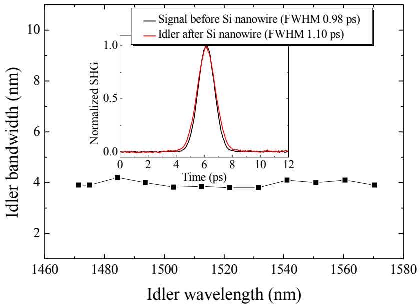

Fig. 5. Measured spectral bandwidth of the converted idler signal with pulsed pump. Inset shows auto-correlator traces for the signal pulse before the silicon waveguide and the converted idler pulse after the silicon waveguide. (The specified FWHMs are for a corresponding Gaussian pulse shape.)

the input of the silicon waveguide, were kept at 20 dBm and -5 dBm, respectively. Fig. 4(a) shows the measured spectra for the TWC with the CW-pump tuning operation. As the pump wavelength shifts, the converted idler wavelength is tuned accordingly. The signal can be down-converted by 135 nm from 1600 nm to 1465 nm with the pump wavelength at 1528 nm, and the converted signal can be tuned over 115 nm (15 THz) from 1580 nm to 1465 nm within the S-, C- and L- bands. The measured conversion efficiency is around -31 dB and only a fluctuation less than 1.8 dB is observed over the whole tuning range as shown in the inset of Fig. 4(a). Compared with the silicon waveguides in references [6] and [14], the estimated achievable conversion bandwidth of our device with pump at zero-GVD wavelength is larger although the conversion efficiency is lower due to the larger propagation loss and shorter interaction length. The conversion efficiency could be improved by reducing the propagation loss through optimization of the fabrication process [15]. The conversion efficiency can also be increased by increasing the peak pump power, i.e. by using a pulsed pump. Fig. 4(b) shows the measured spectra for WC with pulsed-pump tuning operation. The average pump power was fixed at 20 dBm and the average conversion efficiency was increased to around -16.5 dB due to the higher peak pump power as shown in the inset of Fig. 4(b).

We also measured the 3-dB spectral bandwidth of the converted idler signal with pulsed pump as shown in Fig. 5. The average spectral bandwidth is about 3.93 nm with fluctuation less than 0.3 nm. Since the spectral bandwidth of the original signal pulse is 3.9 nm, the converted signal pulse keeps the spectral width and therefore the pulse width of the converted signal is supposed to be almost unchanged. To further test the quality of the idler pulse, we measured the pulse width with an auto-correlator. The inset in Fig. 5 shows the measured pulses with a pump wavelength at 1570 nm before and after the silicon waveguide. The measured FWHM of the converted idler pulse is 1.1 ps which is approximately 10% broader than that of the original signal pulse. The small pulse broadening is mainly due to the filtering effect of the two OBFs and an EDFA before the converted signal is detected by the auto-correlator. This silicon waveguide is thus appropriate for broadband WC, as indeed recently shown with successful 320- and 640-Gbit/s line rate demonstrations [16].

IV. Conclusion

We have demonstrated an ultra-broadband TWC of one-picosecond pulses based on FWM in a 3-mm long silicon waveguide. A tuning range for the converted wavelength of ~115 nm (15 THz) has been obtained with nearly constant conversion efficiency and almost unchanged pulse shape. We believe that the silicon waveguide has potential applications for TWC of ultra-high speed data signals.

Acknowledgment

The authors would like to acknowledge T. Lund-Hansen for fruitful discussions.

References

[1] S. J. B. Yoo, “Wavelength Conversion Technologies for WDM Network Applications,” J. Lightwave Technol., Vol. 14, Jun. 1996, pp. 955-966.

[2] H. Hu, E. Palushani, M. Galili, H. C. H. Mulvad, A. Clausen, L. K. Oxenløwe, and P. Jeppesen, “640 Gbit/s and 1.28 Tbit/s polarisation insensitive all optical wavelength conversion,” Opt. Express, Vol. 18, May. 2010, pp. 9961-9966.

[3] H. Hu, H. Suche, R. Ludwig, B. Huettl, C. Schmidt-Langhorst, R. Nouroozi, W. Sohler, and C. Schubert, “Polarization insensitive all-optical wavelength conversion of 320 Gb/s RZ-DQPSK signals using a Ti:PPLN waveguide,” Appl. Phys. B., Vol. 101, 2010, pp. 875-882.

[4] J. Leuthold, C. Koos and W. Freude, “Nonlinear silicon photonics,” Nat. Photon., Vol. 4, Aug. 2010, pp. 535-544.

[5] S. Zlatanovic, J. S. Park, S. Moro, J. M. Chavez Boggio, I. B. Divliansky, N. Alic and S. Mookherjea and S. Radic, “Mid-infrared wavelength conversion in silicon waveguides using ultracompact telecom band derived pump source,” Nat. Photon., Vol. 4, Aug. 2010, pp. 561-564.

[6] M. A. Foster, A. C. Turner, R. Salem, M. Lipson and A. L. Gaeta, “Broad-band continuous-wave parametric wavelength conversion in silicon nanwaveguides,” Opt. Express, Vol. 15, Oct. 2007, pp. 12949.

[7] H. Rong, Y. H. Kuo, A. Liu and M. Paniccia and O. cohen, “High efficiency wavelength conversion of 10 Gb/s data in silicon waveguides,” Opt. Express, Vol. 14, Feb. 2006, pp. 1182-1188.

[8] N. Ophir, A. Biberman, A. C. Turner-Foster, M. A. Foster, M. Lipson, A. L. Gaeta, and K. Bergman, “First 80-Gb/s and 160-Gb/s Wavelength-Converted Data Stream Measurements in a Silicon Waveguide,” Proc. OFC 2010, paper OWP5.

[9] S. Gao, E. Tien, Q. Song, Y. Huang, and O. Boyraz, “Ultra-broadband one-to-two wavelength conversion using low-phase-mismatching four-wave mixing in silicon waveguides,” Opt. Express, Vol. 18, May. 2010, pp. 11898-11903.

[10] A. C. Turner, C. manolatou, B. S. Schmidt, M. Lipson, M. A. Foster, J. E. Sharping, and A. L. Gaeta, “Tailored anomalous group-velocity dispersion in silicon channel waveguides,” Opt. Express, Vol. 14, 2006, pp. 4357.

[11] E. Dulkeith, F. Xia, L. Schares, W. M. J. Green, and Y. A. Vlasov, “Group index and group velocity dispersion in silicon-on-insulator photonic wires,” Opt. Express, Vol. 14, May 2006, pp. 3835-3863.

[12] M. Pu, L. Liu, H. Ou, K. Yvind, and J.M. Hvam, “Ultra-low-loss inverted taper coupler for silicon-on-insulator ridge waveguide,” Opt. Commun., Vol. 283, Oct. 2010, pp. 3678-3682.

[13] H. Fukuda, K. Yamada, T. Shoji, M. Takhashi, T. Tsuchizawa, T. Watanabe, J. Takahashi, and S. Itabashi, “Four-wave mixing in silicon wire waveguides,” Opt. Express, vol. 13, Jun. 2005, pp. 4629-4637.

[14] M. A. Foster, A. C. Turner, J. E. Sharping, B. S. Schmidet, M. Lipson, A. L. Gaeta, “Broadband optical parametric gain on a silicon photonic chip,” Nature, Vol. 441, Jun. 2006, pp. 960-963.

[15] K. K. Lee, D. R. Lim, L. C. Kimerling, J. Shin, and F. Cerrina, “Fabrication of ultralow-loss Si/SiO_2 waveguides by roughness reduction,” Opt. Lett., Vol. 26, Dec. 2001, pp. 1888-1890.

[16] H. Hu, H. Ji, M. Galili, M. Pu, H.C.H. Mulvad, L. K. Oxenløwe, K. Yvind, J. M. Hvam and P. Jeppesen, “Silicon Chip based Wavelength Conversion of Ultra-High Repetition Rate Data Signals,” Proc. OFC 2011, postdeadline paper PDPA8.